

Heavy neutrino decays at MiniBooNE

Manuel Masip^a, Pere Masjuan^{a,b}, Davide Meloni^c

^a*CAFPE and Departamento de Física Teórica y del Cosmos
Universidad de Granada, 18071 Granada, Spain*

^b*Institut für Kernphysik
Johannes Gutenberg Universität, 55099 Mainz, Germany*

^c*Dipartimento di Fisica ‘E. Amaldi’, Università di Roma Tre
INFN, Sezione di Roma Tre, 00146 Rome, Italy*

masip@ugr.es, masjuan@kph.uni-mainz.de, meloni@fis.uniroma3.it

Abstract

It has been proposed that a sterile neutrino ν_h with $m_h \approx 50$ MeV and a dominant decay mode $\nu_h \rightarrow \nu\gamma$ may be the origin of the experimental anomaly observed at LSND. We define a particular model that could also explain the MiniBooNE excess consistently with the data at other neutrino experiments (radiative muon capture at TRIUMF, T2K, or single photon at NOMAD). The key ingredients are (i) its long lifetime ($\tau_h \approx 3-7 \times 10^{-9}$ s), which introduces a $1/E$ dependence with the event energy, and (ii) its Dirac nature, which implies a photon preferably emitted opposite to the beam direction and further reduces the event energy at MiniBooNE. We show that these neutrinos are mostly produced through electromagnetic interactions with nuclei, and that T2K observations force $\text{BR}(\nu_h \rightarrow \nu_\tau\gamma) \leq 0.01 \approx \text{BR}(\nu_h \rightarrow \nu_\mu\gamma)$. The scenario implies then the presence of a second sterile neutrino $\nu_{h'}$ which is lighter, longer lived and less mixed with the standard flavors than ν_h . Since such particle would be copiously produced in air showers through $\nu_h \rightarrow \nu_{h'}\gamma$ decays, we comment on the possible *contamination* that its photon-mediated elastic interactions with matter could introduce in dark matter experiments.

1 Introduction

Although we have today evidence that neutrinos have masses and mixings [1], there are still basic questions that past experiments have been unable to answer. The most important one concerns their Dirac or Majorana nature: Are neutrino masses purely electroweak (EW) or they are revealing a new fundamental scale? Other questions like CP violation or the presence of extra neutrino species often use minimality as guiding principle, an argument that has worked well in the quark sector. In this sense, the three-flavor framework with $\Delta m_{12}^2 \approx 7.9 \times 10^{-5} \text{ eV}^2$, $\Delta m_{23,13}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2$ and mixings $\sin^2 \theta_{12} \approx 0.30$, $\sin^2 \theta_{23} \approx 0.50$, $\sin^2 \theta_{13} \approx 0.01$ seems to fit well the data from solar, atmospheric and reactor experiments.

This basic picture, however, has faced a series of *persistent* anomalies in experiments with neutrino beams from particle accelerators. Basically, muon neutrinos of energy below 1 GeV seem to experience an excess of charged-current (CC) interactions with an electron in the final state. The interpretation of these events in terms of $\nu_\mu \rightarrow \nu_e$ oscillations would require the presence of (several) sterile neutrinos [2], and it fits only marginally the combined results of LSND, KARMEN and MiniBooNE.

Here we will discuss a very different possibility. In particular, we will explore a variation of the heavy-neutrino model proposed in [3] to explain the LSND/KARMEN anomaly. LSND [4] was designed to observe the interaction of muon antineutrinos of $E_\nu \leq 52 \text{ MeV}$ after a 30 m flight. The results revealed an excess that was interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations followed by a CC quasi-elastic interaction giving an observable e^+ and a free neutron. The neutron would then be captured to form a deuteron plus an also observable 2.2 MeV photon. The LSND signal, however, was not confirmed by KARMEN [5] using a similar technique.

In [3] Gninenko makes a very compelling case for a massive neutrino as a possible solution to the LSND/KARMEN puzzle. In addition to the $\bar{\nu}_\mu$'s from the decay-at-rest of μ^+ leptons, the LSND flux included 60–200 MeV muon neutrinos from the decay-in-flight of π^+ mesons. In KARMEN, however, the location of the detector (defining a large angle relative to the incident proton beam) eliminates these neutrinos, selecting only antineutrinos of $E \leq m_\mu/2$. A 40–80 MeV sterile neutrino ν_h would then be above the production threshold there but not at LSND. Gninenko shows that if ν_h has a sizable component along the muon flavor ($|U_{\mu h}|^2 \approx 10^{-3}$ – 10^{-2}) it could explain the LSND excess provided that it decays fast enough ($\tau_h \leq 10^{-8} \text{ s}$) into a light neutrino ν_i plus a photon,

$$\nu_h \rightarrow \nu_i \gamma. \quad (1)$$

He argues that the Cherenkov light from a photon converted into a e^+e^- pair would be indistinguishable from that of an electron, and shows that the neutron hit by the initial ν_μ

has the *right* recoil to provide the correlated 2.2 MeV photon.

In Gninenko's scenario the production of the heavy neutrino is fixed by the mixing $U_{\mu h}$, whereas the lifetime depends on the electromagnetic (EM) coupling μ_{tr} (see next Section). One can then easily estimate its effects in other experiments. In particular, ν_h will be produced at MiniBooNE via Z exchange with the nucleons in the detector. Gninenko finds [3] that in order to have an impact there its lifetime must be reduced to $\tau_h \leq 10^{-9}$ s, a decade below the maximum value suggested by LSND. The large $U_{\mu h}$ mixing required to explain these two experiments, however, will also introduce CC transitions ($\mu \rightarrow \nu_h$) with experimental implications. In [6] it is shown that the model would conflict with observations of muon capture with photon emission at TRIUMF [7], implying a signal well above the 30% excess (versus the standard model value) deduced from the data.

Here we propose the possibility that ν_h has a *longer* lifetime, of order $3\text{--}7 \times 10^{-9}$ s, and that its dominant production channel at MiniBooNE is through photon (instead of Z) exchange with matter. The main effect of an increased τ_h is easy to understand. At TRIUMF the target volume is much smaller than $c\tau_h$, and the number of events with ν_h decaying inside the detector,

$$\mu^- p \rightarrow \nu_h n \rightarrow \nu_i \gamma n, \quad (2)$$

is proportional to $1/\tau_h$. Therefore, an increase in the lifetime by a factor of 3–7 respect to the value assumed in [6] will reduce the number of events by the same factor. The larger lifetime will also reduce the number of events at MiniBooNE. However, as noticed in [6], the EM couplings necessary to mediate ν_h decay may also have an impact on its production, and we will use them to compensate this reduction. In addition, since the decay length λ_d of the heavy neutrino grows linear with its energy,

$$\lambda_d = c\tau_h \frac{E_h}{m_h} \sqrt{1 - \frac{m_h^2}{E_h^2}}, \quad (3)$$

the effect of a larger τ_h will be stronger on high than on low-energy events at MiniBooNE. The energy dependence that we will obtain fits better the data there than neutrino oscillations or the prompt ν_h -decay hypothesis by Gninenko.

In the next sections we define a model for the heavy neutrino and explore its implications at MiniBooNE. In section 4 we study the impact of the model on T2K, which further constrains the scenario and defines a *working* model. Finally, in section 5 we summarize our results and discuss the possible implications of the scenario in other experiments.

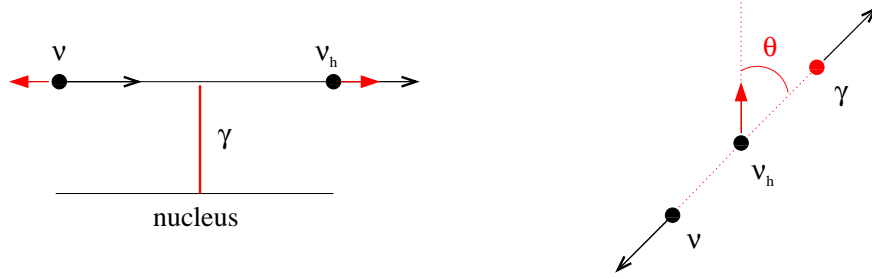


Figure 1: Heavy neutrino production $\nu Z \rightarrow \nu_h Z$ through photon exchange with a nucleus (left) and decay $\nu_h \rightarrow \nu \gamma$ (right).

2 The heavy neutrino

We will assume that ν_h is a Dirac particle of mass $m_h = 50$ MeV with a left-handed component slightly mixed with the muon neutrino:

$$\begin{aligned}\nu'_h &= \cos \theta \nu_h + \sin \theta \nu_\mu, \\ \nu'_\mu &= -\sin \theta \nu_h + \cos \theta \nu_\mu,\end{aligned}\tag{4}$$

where $\sin \theta = U_{\mu h}$ and $|U_{\mu h}|^2 = 0.003$. We will also assume that the heavy neutrino does not introduce any new sources of lepton-number violation. If the light neutrinos ν_i ($i = e, \mu, \tau$) are Dirac particles this assumption will not have any implications on the $\nu_i \rightarrow \nu_h$ EM transitions. If they are Majorana, however, it implies a relation between the electric and the magnetic dipole transitions,

$$L_{eff} \subset \frac{1}{2} \mu_{tr}^i \left(\bar{\nu}_h \sigma_{\mu\nu} (1 - \gamma_5) \nu_i + \bar{\nu}_i \sigma_{\mu\nu} (1 + \gamma_5) \nu_h \right) \partial^\mu A^\nu,\tag{5}$$

where we have dropped the prime to indicate mass eigenstates and have taken a real value for the coupling μ_{tr}^i . The Lagrangian above is then CP conserving, it only breaks parity. We will use it to calculate the production and the decay (in Fig. 1) of the heavy neutrino ν_h . Since the masses of the light neutrinos are negligible at MiniBooNE energies, lepton number will be preserved both in EW processes and in the production or the decay of ν_h , and the light neutrinos ν_i ($\bar{\nu}_i$) will always appear with negative (positive) helicity.

Production cross section. The production of the heavy neutrino in ν_μ collisions with matter will include Z - and photon-mediated processes. The first ones, with an amplitude proportional to $U_{\mu h}$, will couple ν_μ to the protons and the neutrons in the target oil (CH_2) at MiniBooNE (collisions with electrons are negligible). We will show, however, that long-distance processes mediated by the massless photon, with an amplitude proportional to μ_{tr}^μ , may be the dominant ones.

Let us consider the quasi-elastic production of ν_h through photon exchange when a neutrino of energy E_ν scatters off a nucleus of charge Z and mass M . The initial neutrino results from a meson or a muon decay, and it will always be polarized against the beam direction (i.e., it has a negative helicity). If the target is a spin 1/2 nucleus the cross section reads

$$\frac{d\sigma(\nu_\mu Z \rightarrow \gamma \nu_h)}{dt} = \frac{\alpha Z^2 F^2(t) (\mu_{\text{tr}}^\mu)^2}{2} \frac{f(s, t)}{t^2 (s - M^2)^2} \quad (6)$$

where $s = M^2 + 2E_\nu M$, $t = (p_{\nu_h} - p_\nu)^2$, $F(t)$ is the form factor, and

$$f(s, t) = -2t(s - M^2)(s - M^2 + t) + m_h^2 t(2s + t) - m_h^4 (2M^2 + t). \quad (7)$$

If the target is a spin 0 nucleus (like ^{12}C) the cross section can be obtained just by replacing the term $-m_h^4$ in $f(s, t)$ by $-t^2(t + m_h^2/2)$. The Mandelstam variable t is simply related to the recoil energy T of the nucleus,

$$T = -\frac{t}{2M}, \quad (8)$$

whereas the scattering angle θ in the lab frame is

$$\cos \theta = \frac{E_\nu - T - \frac{MT}{E_\nu} - \frac{m_h^2}{2E_\nu}}{\sqrt{E_\nu^2 + T^2 - 2E_\nu T - m_h^2}}. \quad (9)$$

Notice also that if the neutrino ν_h were massless, it would be always produced as a right-handed particle of positive helicity, since the EM transition would flip the chirality. The final state with negative helicity gives a contribution of order $(m_h/E_\nu)^2$ to the cross section above. For $m_h = 50$ MeV, at 700 MeV we find that only one out of 5×10^5 massive neutrinos will have the spin against its momentum. In contrast, the ν_h produced at MiniBooNE through Z exchange will have the opposite (negative) helicity.

In addition to the helicity of the final neutrino, the main difference between Z and photon-mediated processes is the typical distance (or equivalently, the $q^2 = -t$ or the recoil T) in the collision. In Fig. 2-left we plot the distribution $((T/\sigma) d\sigma/dT)$ for $\nu_\mu p \rightarrow \nu_h p$ at $E = 700$ MeV. We find that the average recoil is $T = 150$ MeV when the collision is mediated by a Z boson but just 2 MeV in processes that go through photon exchange.

For form factor $F(t)$ describing the target we have used the expresions in [8]. At q^2 between 10^{-9} and 10^{-3} GeV^2 , which are dominant in these photon-mediated collisions, the incident neutrino interacts coherently with the whole nucleus. At lower values of q^2 electrons tend to screen the nuclear electric charge, whereas at higher values the collision is mainly with the protons inside the nucleus (we use then the usual EM form factors [9]). In Fig. 2-right we plot the total cross section for the quasi-elastic process $\nu_\mu \text{CH}_2 \rightarrow \nu_h \text{CH}_2$ for $U_{\mu h}^2 = 0.003$ and $\mu_{\text{tr}}^\mu = 2.4 \times 10^{-9} \mu_B$ (see below).

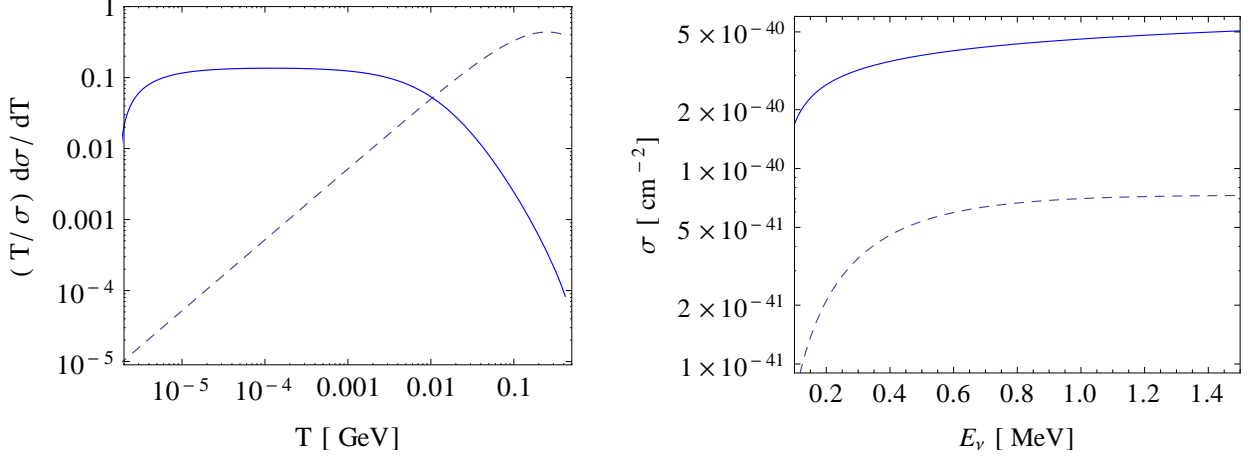


Figure 2: Left: $\frac{T}{\sigma} \frac{d\sigma}{dT}$ for $\nu_\mu p \rightarrow \nu_h p$ through photon (solid) and Z (dashes) exchange for $E_\nu = 0.7$ GeV. Right: Total cross section $\sigma(\nu_\mu \text{ CH}_2 \rightarrow \nu_h \text{ CH}_2)$ for $U_{\mu h}^2 = 0.003$ and $\mu_{\text{tr}}^\mu = 2.4 \times 10^{-9} \mu_B$.

Decay rate. For the decay $\nu_h \rightarrow \nu_i \gamma$ (in Fig. 1-right), let us consider a neutrino ν_h at rest and with spin $|+\rangle$ along the Z direction. It is easy to find [10, 11] the angular distribution of the final photon:

$$\frac{d\Gamma}{d\cos\theta} = \frac{\mu_{\text{tr}}^2}{32\pi} m_h^3 (1 - \cos\theta) \quad (10)$$

where $\mu_{\text{tr}}^2 = \sum_i (\mu_{\text{tr}}^i)^2$ and θ is the angle between the photon momentum and the Z axis. Therefore, the photon prefers to exit against the spin of the initial heavy neutrino. Analogously, when the particle decaying is an antineutrino $\bar{\nu}_h$ the final photon will be more frequently emitted along the direction of the spin.

For a neutrino mass $m_h = 50$ MeV, the lifetime $\tau_h = 5 \times 10^{-9}$ s is obtained with $\mu_{\text{tr}} = 7.2 \times 10^{-6} \text{ GeV}^{-1} = 2.4 \times 10^{-8} \mu_B$. This is a relatively *large* value of μ_{tr} , as it will be generated at one loop and must include a fermion-mass insertion. The ultraviolet completion of our ν_h scenario would then require the presence of extra physics at the TeV scale (see, for example, the left-right symmetric models in [11]).

When the decay $\nu_h \rightarrow \nu_i \gamma$ includes several neutrino species ($i = \mu, \dots$) the branching ratios are just $\text{BR}_i = (\mu_{\text{tr}}^i)^2 / \mu_{\text{tr}}^2$. Notice also that since the beam at MiniBooNE is composed of (mostly) muon neutrinos, the production cross section through photon exchange is just sensitive to $(\mu_{\text{tr}}^\mu)^2$.

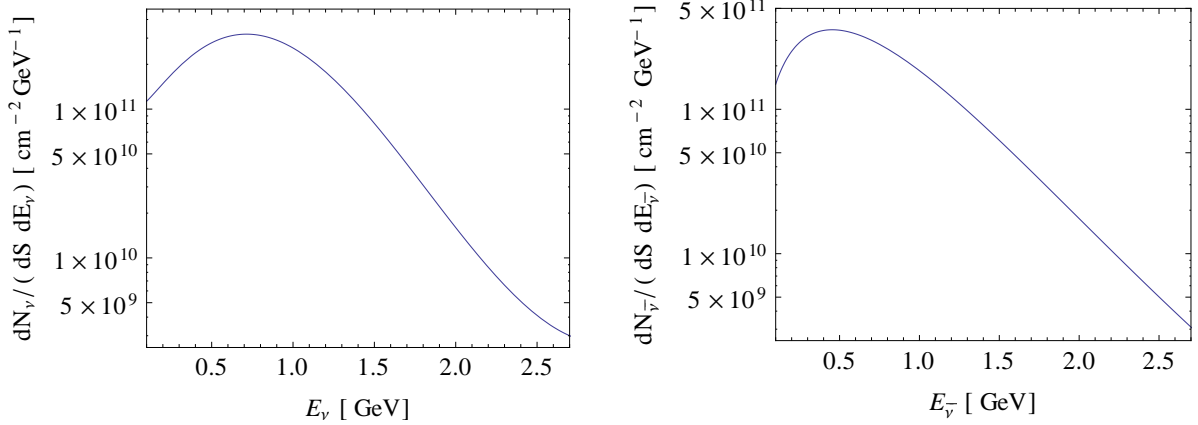


Figure 3: Flux at MiniBooNE in the neutrino mode for 5.58×10^{20} POT (left) and in the antineutrino mode for 11.27×10^{20} POT (right).

3 Heavy neutrino events at MiniBooNE

MiniBooNE [12] has run in neutrino [13] and antineutrino [14] modes. We will first analyze the results for neutrinos from 6.46×10^{20} protons on target (POT) presented in [13]. These data were initially used by MiniBooNE to *exclude* the neutrino oscillation hypothesis favored by LSND (see below), although latter analyses emphasized the anomaly observed at low energies [13]. We will also estimate our prediction for MiniBooNE in the antineutrino mode with an exposure to 11.27×10^{20} POT [15], where the data seems more consistent with the 3+1 neutrino-oscillation picture. Our fit to the total muon neutrino flux $dN_\nu/(dS dE_\nu)$ [12] in these two cases is given in Fig. 3.

MiniBooNE is a sphere of fiducial radius $R \approx 5$ m filled up with CH_2 of density $\rho = 0.86$ g/cm³. When a neutrino enters the detector it finds an oil column of length L , with L taking values between 0 and $2R$ depending on the point of entrance (see Fig. 4). To define an observable ν_h event, first ν_μ must interact at a distance $l < L$ from the entrance and produce the heavy neutrino, and then ν_h must decay within a distance $L - l$, *i.e.*, before leaving the fiducial volume. It is easy to see that, while the probability to interact is just

$$p_i = \frac{\sigma \rho L}{m_{\text{CH}_2}}, \quad (11)$$

the probability to interact *and* decay within the distance L becomes

$$p_{i+d} = \frac{\sigma \rho L}{m_{\text{CH}_2}} \left(1 - \frac{\lambda_d}{L} \left(1 - e^{-\frac{L}{\lambda_d}} \right) \right), \quad (12)$$

where the decay length λ_d , defined in Eq. (3), depends on the heavy neutrino energy $E_h =$

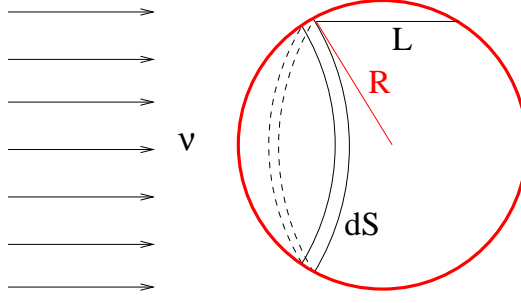


Figure 4: Geometry of the detector at MiniBooNE.

$E_\nu - T$ and its lifetime τ_h . Since the photon-mediated processes under study introduce small recoils, in our estimate we will consider that ν_h is produced forward and with energy $E_h = E_\nu$. Integrating over all the points of entrance into the detector we obtain that the energy distribution of heavy neutrinos decaying inside MiniBooNE is

$$\frac{dN_h}{dE_\nu} = \frac{dN_\nu}{dS dE_\nu} \frac{\sigma V \rho}{m_{CH_2}} \int_0^1 dy \left(1 - \frac{\lambda_d}{2Ry^{1/3}} \left(1 - e^{-\frac{2Ry^{1/3}}{\lambda_d}} \right) \right), \quad (13)$$

where $V = 4\pi R^3/3$, $m_{CH_2} = (14/6.022) \times 10^{-23}$ g and the energy dependence of the total cross section σ and of λ_d is understood.

The ν_h energy distribution dN_h/dE_ν above must then be translated into a distribution of visible energy. As explained in the previous section, most of the neutrinos ν_h produced via photon exchange have positive helicity, and when they decay $\nu_h \rightarrow \nu_i \gamma$ the gamma tends to exit backwards. If ν_h carries E_ν , Eq.(10) implies that in the lab frame the energy of the final photon will be distributed linearly between $E_{\min} = E_\nu(1 - \beta)/2$ and $E_{\max} = E_\nu(1 + \beta)/2$, with $\beta = \sqrt{1 - m_h^2/E_\nu^2}$. The distribution of $x = E_\gamma/E_\nu$ is then just

$$f(x) = \frac{2}{x_{\max} - x_{\min}} - 2 \frac{x - x_{\min}}{(x_{\max} - x_{\min})^2}, \quad (14)$$

with $x_{\min(\max)} = E_{\min(\max)}/E_\nu$. In Fig. 5 we plot $f(x)$ for $E_\nu = 0.7$ GeV and $m_h = 50$ MeV. The energy distribution dN_h/dE_γ of the photons from heavy-neutrino production and decay is then obtained from the integral

$$\frac{dN_h}{dE_\gamma} = \int_0^1 dx \frac{dN_h}{dE_\nu}(E_\gamma/x) \frac{f(x)}{x}, \quad (15)$$

where dN_h/dE_ν is evaluated at $E_\nu = E_\gamma/x$.

In [13] the results are presented in terms of the energy of the incident neutrino, which is reconstructed from the visible energy and the scattering angle of the final electron. In the

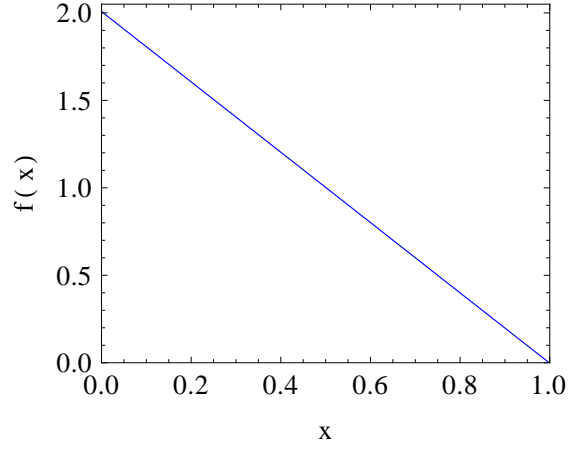


Figure 5: Fraction of energy taken by γ in $\nu_h \rightarrow \nu_i \gamma$ ($E_\nu = 0.7$ GeV, $m_h = 50$ MeV).

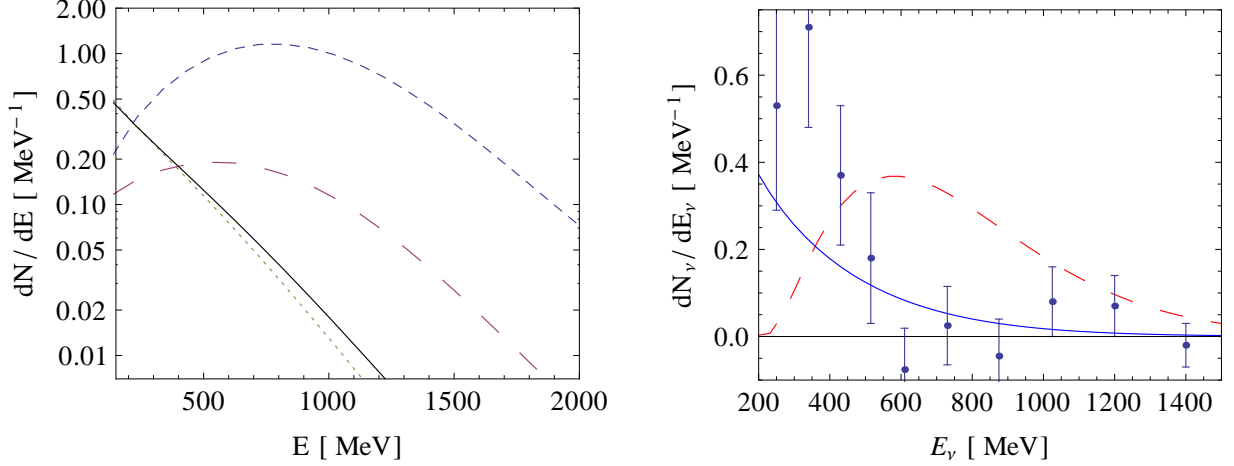


Figure 6: Left: Energy distribution of heavy neutrinos produced in the detector (dashes), of heavy neutrinos decaying inside the detector (long dashes), of photons from $\nu_h \rightarrow \nu_i \gamma$ (dots), and of ν_h events reconstructed as CC interactions (solid). Right: Energy distribution of ν_h events reconstructed as CC interactions (solid), of events from neutrino oscillations for $\sin^2(2\theta) = 0.004$ and $\Delta m^2 = 1$ eV² (long dashes), and excess observed by MiniBooNE in the neutrino mode.

events under study here the final photon will typically exit forward, defining a small angle. For example, in average a 400 MeV neutrino would produce through photon exchange a ν_h with an angle of 7° , and its decay would add 22° to the final photon trajectory. In contrast, a W -mediated process would imply an electron with an average angle of 65° (see [16, 17] for a study of quasielastic neutrino scattering). In Fig. 6–left we plot the energy distribu-

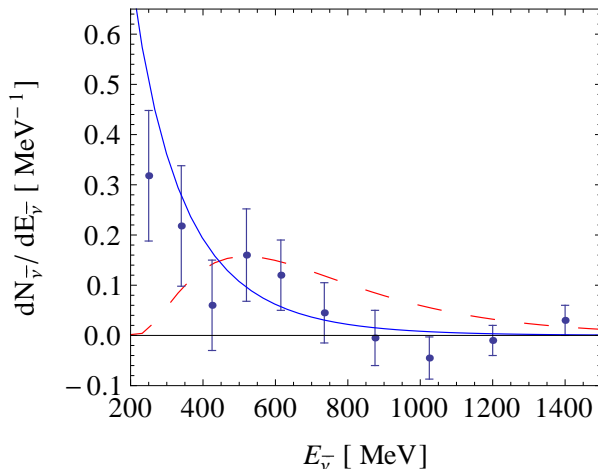


Figure 7: Energy distribution of ν_h events reconstructed as CC ν interactions (solid), of events from neutrino oscillations for $\sin^2(2\theta) = 0.004$ and $\Delta m^2 = 1 \text{ eV}^2$ (long dashes), and excess observed by MiniBooNE in the antineutrino mode (with error bars).

tion dN/dE of neutrinos ν_h produced inside the detector, of neutrinos that decay inside the detector, of photons from ν_h decays, and of the neutrinos that one would reconstruct assuming that the visible energy comes from a CC interaction. These results include the events where ν_h is produced through Z exchange, which for $U_{\mu h}^2 = 0.003$ account for just a 12% of the total. We have taken $\tau_h = 5 \times 10^{-9} \text{ s}$ and $\text{BR}_\mu = 0.01$, which correspond to $\mu_{\text{tr}}^\mu = 2.4 \times 10^{-9} \mu_B$.

In Fig. 6–right we summarize our results for MiniBooNE in the neutrino mode. We give the energy distribution of the ν_h events reconstructed as W -mediated interactions together with the distribution expected from neutrino oscillations for $\sin^2(2\theta) = 0.004$ and $\Delta m^2 = 1 \text{ eV}^2$ and the excess observed at MiniBooNE. These oscillation parameters had been favored by the LSND anomaly, but they imply a 500–700 MeV excess that was initially excluded by MiniBooNE. In contrast, the long-lived heavy neutrino hypothesis seems consistent with the data.

In Fig. 7 we plot the results from an analogous analysis for 11.27×10^{20} POT in the antineutrino mode of MiniBooNE [15]. The data at 500–700 MeV seem to favor the LSND oscillation hypothesis, although the excess observed at lower energies would still remain unexplained. Our long-lived heavy neutrino, instead, provides a reasonable fit at all energies.

4 T2K implications

LSND and MiniBooNE led us to define a model for ν_h where the EM transition that fixes its lifetime, $\mu_{\text{tr}} = 2.4 \times 10^{-8} \mu_B$, is 10 times larger than the coupling required to produce it at MiniBooNE, $\mu_{\text{tr}}^\mu = 2.4 \times 10^{-9} \mu_B$. This implies that the branching ratio for the decay into the muon-neutrino flavor ($\nu_h \rightarrow \nu_\mu \gamma$) is just around 1%. The obvious question is then what other flavor may account for 99% of the decays, and the tau neutrino seems the natural candidate.

To check the consistency of this possibility one needs a ν_τ beam, and the long-baseline experiment T2K [18, 19] provides such a beam. Muon neutrinos are produced at Tokai with $E_\nu \approx 0.6$ GeV and they travel 295 km to Super-Kamiokande, where most of them have oscillated into the tau flavor:

$$p_{\nu_\mu \rightarrow \nu_\tau} \approx \sin^2 2\theta_{23} \sin^2 \frac{1.27 \Delta m_{23}^2 (\text{eV}^2) L (\text{km})}{E_\nu (\text{GeV})}, \quad (16)$$

with $\sin^2 2\theta_{23} \approx 1$ and $\Delta m_{23}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2$. Therefore, T2K would be able to measure the θ_{13} angle through oscillations of muon into electron neutrinos,

$$p_{\nu_\mu \rightarrow \nu_e} \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{1.27 \Delta m_{23}^2 (\text{eV}^2) L (\text{km})}{E_\nu (\text{GeV})}, \quad (17)$$

but also the anomalous EM interactions of ν_τ with matter to produce the heavy neutrino ν_h [20] (see also [21] for possible effects of ν_h on tau physics).

The inner detector (ID) at Super-Kamiokande is a cylindrical tank with a fiducial volume of radius $R = 17$ m and 32 m high (*i.e.*, 22.6 tones of pure water). An outer detector (OD) enclosing the tank excludes events with activity at distances below 4.5 m from the fiducial volume in the ID. Therefore, there are two ways to generate a signal through ν_h decays. The heavy neutrino could be produced in the rock before the detector, fly through the OD and decay inside the fiducial volume in the ID, or it could both be produced and decay inside the ID.

If only muon neutrinos can produce ν_h through photon exchange (*i.e.*, $\mu_{\text{tr}}^\mu = 2.4 \times 10^{-9} \mu_B$, $\mu_{\text{tr}}^\tau = 0$), the energy distribution of the heavy neutrinos that are produced and decay inside the ID is

$$\frac{dN_h}{dE_\nu} = \frac{dN_\nu}{dS dE_\nu} \frac{\sigma V \rho (1 - p_{\nu_\mu \rightarrow \nu_\tau})}{m_{H_2O}} \int_0^{\pi/2} d\theta \frac{4 \cos^2 \theta}{\pi} \left(1 - \frac{\lambda_d}{2R \cos \theta} \left(1 - e^{-\frac{2R \cos \theta}{\lambda_d}} \right) \right), \quad (18)$$

where λ_d is defined in Eq. (3), σ is the cross section to produce a ν_h in the collision of ν_μ with water, $\rho = 1 \text{ g/cm}^3$, and we have taken the neutrino flux $dN_\nu/dS dE_\nu$ in [19]. For

comparison, the distribution of ν_e producing electrons in collisions with water would just be

$$\frac{dN_e}{dE_\nu} = \frac{dN_\nu}{dS dE_\nu} \frac{\sigma_{CC} V \rho p_{\nu_\mu \rightarrow \nu_e}}{m_{H_2O}}. \quad (19)$$

The calculation of the energy distribution of the neutrinos produced in the surrounding rock (beyond a distance $D_0 = 4.5$ m of the ID) and decaying inside the detector is also straightforward,

$$\frac{dN'_h}{dE_\nu} = \frac{dN_\nu}{dS dE_\nu} \frac{\sigma V \rho_r (1 - p_{\nu_\mu \rightarrow \nu_\tau})}{m_r} \frac{2 \lambda_d e^{-\frac{D_0}{\lambda_d}}}{\pi R} \int_0^{\pi/2} d\theta \cos \theta \left(1 - e^{-\frac{2R \cos \theta}{\lambda_d}} \right), \quad (20)$$

where we have taken $\rho_r = 3.2$ g/cm³.

We obtain that whereas $\nu_\mu \rightarrow \nu_e$ oscillations with $\sin^2 2\theta_{13} = 0.1$ would imply 6 events of energy above 100 MeV, ν_μ collisions producing a ν_h that decays into $\nu_i \gamma$ would introduce 1.1 events, 75% of them from heavy neutrinos created in the rock and decaying inside the detector. These *long-flying* neutrinos dominate over the ones produced inside the detector due to the larger density of the soil surrounding the detector and the relatively long lifetime ($\lambda_d = 15$ m for $E_h = 500$ MeV) of ν_h . Therefore, in our framework the MiniBooNE anomaly could also *contribute* to the signal observed at T2K [19], implying a smaller value of the mixing θ_{13} . The contribution would be larger for a non-zero value of the coupling μ_{tr}^τ that defines the $\nu_\tau \rightarrow \nu_h$ EM transitions. Since these ν_h events have different kinematical and energy distributions, it seems clear that an increased statistics there could disregard this possibility. Incidentally, the events with ν_h produced in the rock would be distributed preferably near the point of entrance into the detector (the distribution is proportional to e^{-D/λ_d}), as it has been observed, whereas the $\nu_\mu \rightarrow \nu_e$ oscillation hypothesis implies a flat distribution.

The previous result also implies that $\mu_{tr}^\tau \leq \mu_{tr}^\mu$. In particular, if the channel $\nu_h \rightarrow \nu_\tau \gamma$ accounted for 99% of the ν_h decays, then the number of electron-like events at T2K from $\nu_\tau Z \rightarrow \nu_h Z$ EM transitions would be around 240, well above the 6 events that were observed. As a consequence, to be viable the model requires an additional sterile¹ neutrino $\nu_{h'}$ which is lighter than ν_h and has the coupling $\mu_{tr}^{h'} \approx 2.4 \times 10^{-8} \mu_B$ required to mediate $\nu_h \rightarrow \nu_{h'} \gamma$ at the right rate ($\tau_h \approx 5 \times 10^{-9}$ s).

Finally, we would like to comment on the signal that the model could imply at the near detector (ND280) [18] in T2K. When the neutrino beam reaches the off-axis detector at ND280 it has not changed its muon flavor yet. A typical event would consist of an initial

¹The electron flavor seems also disfavored, since the process $\nu_e Z \rightarrow \nu_h Z$ with $\nu_h \rightarrow \nu_e \gamma$ in the atmosphere would introduce a signal identical to ν_e CC interactions.

interaction producing the heavy neutrino ν_h and a small energy deposition (a 10 keV–10 MeV nuclear recoil) in the Pi-zero detector, followed by the single photon from its decay at any point in the tracking system (three TPCs and two thinner FGDs). We estimate around 2.1 events of this type per 1000 ν_μ CC interactions, plus 0.8 events with the ν_h both being produced and decaying inside the Pi-zero detector. In the tracker the photon would convert into an e^+e^- pair that could be distinguished from the single electron plus recoil in a CC interaction, whereas events with neutral pions giving two photons seem also clearly different. Therefore, ND280 may provide some ground to probe the MiniBooNE/LSND anomaly and establish its electron or photon origin (if any).

5 Summary and discussion

LSND observed an excess of $\approx 3 \times 10^{-3}$ interactions with an electron in the final state per each $\bar{\nu}_\mu$ CC event. The beam in this experiment included antineutrinos of $E < 60$ MeV from the decay-at-rest of μ^+ leptons but also neutrinos of up to 200 MeV. KARMEN tried then to confirm the LSND anomaly using a beam that excluded the high-energy region of the spectrum, and it did not see such an excess.

Gninenko has proposed that the LSND anomaly could be explained by a 50 MeV neutrino, a mass which is beyond the reach at KARMEN. This hypothesis requires that ν_h decays into $\nu_i\gamma$ with $\tau_h \leq 10^{-8}$ s and that the production mechanism is mediated by the Z boson (or other massive particle), as the q^2 in the collision must be large enough to produce the free neutron also detected at LSND.

A similar rate of anomalous interactions (3×10^{-3} per ν_μ CC event) has also been observed at MiniBooNE both in the neutrino and the antineutrino modes. In contrast with LSND, the energy distribution of these events does not seem consistent with a simple 3+1 oscillation scheme, as it peaks at low energy (where the $\nu_\mu \rightarrow \nu_e$ probability vanishes) and is non-significant at the expected oscillation maximum. The initial neutrino data were actually used by MiniBooNE to exclude the oscillation hypothesis favored by LSND. Although the first MiniBooNE results in the antineutrino mode were *different* and could favor a 3+1 scheme, the increased statistics obtained during the 2011 run (in Fig. 7) shows consistency with the observations in the neutrino mode (in Fig. 6–right).

Gninenko’s hypothesis can have an impact at MiniBooNE only if the lifetime of the heavy neutrino is reduced below 10^{-9} s (versus the maximum 10^{-8} s required at LSND). The energy distribution that it implies is *better* than the one obtained from oscillations, but probably still a bit flatter than the one observed at MiniBooNE. In Fig. 8 we plot Gninenko’s

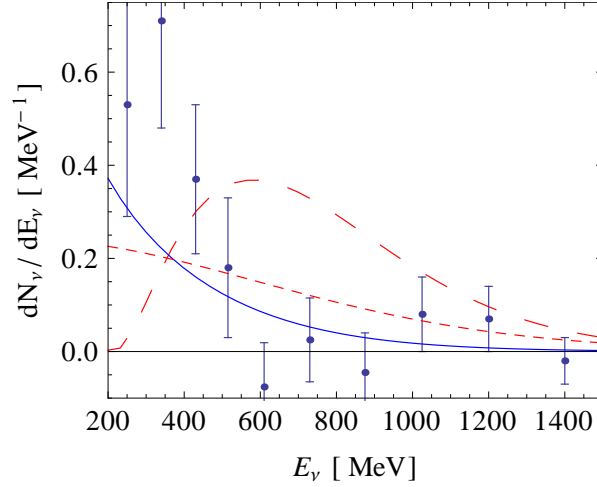


Figure 8: Energy distribution of ν_h events in the Gninenko model ($|U_{\mu h}|^2 = 0.007$, $\tau_h = 10^{-9}$ s, $\mu_{\text{tr}}^\mu = 0$) (dashes), in our set up ($|U_{\mu h}|^2 = 0.003$, $\tau_h = 5 \times 10^{-9}$ s, $\mu_{\text{tr}}^\mu = 2.4 \times 10^{-9} \mu_B$) (solid), distribution of events from neutrino oscillations for $\sin^2(2\theta) = 0.004$ and $\Delta m^2 = 1 \text{ eV}^2$ (long dashes), and excess observed by MiniBooNE in the neutrino mode.

model for a Majorana ν_h with $|U_{\mu h}|^2 = 0.007$ and $\tau_h = 10^{-9}$ s. If ν_h were a Dirac particle its distribution would be even flatter, as ν_h has then negative helicity and decays predominantly into a forward photon. At any rate, the mixing and the lifetime in Gninenko's model implies too many events with radiative muon capture at TRIUMF [6].

Our initial observation is that the coupling required to explain the decay of ν_h may also imply its production through photon exchange with matter. While the lifetime is a measure of $\mu_{\text{tr}}^2 = \sum_i (\mu_{\text{tr}}^i)^2$, where i runs over all the light neutrino flavors, the production rate at MiniBooNE depends on μ_{tr}^μ only. The photon-mediated production of ν_h will not contribute significantly to the anomaly at LSND, as the interaction is unable to free a neutron from its nucleus (it involves charged particles and is very soft).

Therefore, we keep the mixing $|U_{\mu h}|^2 \approx 0.003$, required to explain LSND through Z -mediated interactions, but we also increase the lifetime τ_h by a factor of 3–7. First of all, this reduces in the same proportion the number of CC events with ν_h decaying inside the detector at TRIUMF, providing for consistency with this experiment. Second, the number of ν_h decays at MiniBooNE will also be reduced, but this can be compensated by the larger number of heavy neutrinos obtained from photon-mediated processes. Finally, the longer lifetime implies that low-energy neutrinos are more likely to decay inside the MiniBooNE detector than the more energetic ones. In addition, the negative helicity of the initial ν_μ implies that the EM transition produces a (Dirac) ν_h polarized forward, with positive helicity,

and that the final photon is emitted preferably backwards. These two factors define a spectrum that seems consistent with the observations at MiniBooNE.

The scenario implies that $\nu_h \rightarrow \nu_\mu \gamma$ accounts for just around 1% of the decays, and T2K forces that the branching ratio for $\nu_h \rightarrow \nu_\tau \gamma$ is even smaller. In any case, an increased statistics at T2K could be used to probe the model. Other experiments could also put important constraints. Most notably, NOMAD [22] has recently set bounds (not discussed in previous sections) on single photon events in neutrino interactions at ≈ 25 GeV. Although Gninenko [23] has shown the consistency of his model with the data, our scenario involves larger lifetimes and production cross sections for the heavy heavy neutrino. The increase in τ_h will introduce two competing effects that tend to cancel each other: the heavy neutrinos produced in the rock are less likely to decay inside the detector, but they can be produced further from the detector and still reach it. We estimate that for $\tau_h = 5 \times 10^{-9}$ s our model implies around 2×10^{-4} events per each ν_μ CC event (above the 1.6×10^{-4} limit established there). While lower values $\tau_h \approx 3 \times 10^{-9}$ s would be *safer*, a more definite statement would require a full MonteCarlo simulation.

Since the dominant decay channel $\nu_h \rightarrow \nu_i \gamma$ is not into the muon nor the tau flavors and the electron flavor seems also disfavoured, an interesting possibility would be that the heavy neutrino decays into a photon plus *another* sterile heavy neutrino $\nu_{h'}$. The mixing of this second neutrino with the standard flavors could be much smaller than the one required for ν_h ($|U_{\mu h}|^2 = 0.003$), while a 5–10 MeV mass and a lifetime below 1 s would make it consistent with bounds from astrophysics and cosmology [24]. It could decay $\nu_{h'} \rightarrow \gamma \nu_{e,\mu,\tau}$ with $c\tau_{h'} > 10$ km. Such a long lifetime would make it very frequent in the atmosphere [25]: it would be produced in $\nu_h \rightarrow \nu_{h'} \gamma$, with the parent ν_h appearing in $\approx 0.3\%$ of all kaon and muon decays [3]. Such neutrino could also have a relatively large EM dipole moment, able to mediate elastic interactions $\nu_{h'} Z \rightarrow \nu_{h'} Z$ with a cross section softer but orders of magnitude larger than the ones mediated by the Z boson. In particular, at 1–100 MeV energies one could expect collisions with the typical recoils (few keV) in dark matter experiments. We think that it would be interesting to analyze to what extent such neutrino could *contaminate* experiments like DAMA/LIBRA [26] or CoGeNT [27]. A similar effect caused by solar neutrinos oscillating into a sterile flavor has been discussed in [28, 29]

To conclude, although the current framework for neutrino masses and mixings explains most of the experimental data, the picture that we have today is still far from complete. The possibility that neutrinos involve new physics at the MeV, a scale that we have been exploring for many decades, may sound unlikely or unappealing. We think, however, that it should be considered, specially as long as the current experimental anomalies persist.

Acknowledgments

We would like to thank Antonio Bueno, Claudio Giganti and Patricia Sánchez-Lucas for discussions. This work has been partially supported by MICINN of Spain (FPA2010-16802 and Consolider-Ingenio **Multidark** CSD2009-00064 and **CPAN** CSD2007-00042), by Junta de Andalucía (FQM 101, FQM 437 and FQM 3048), by DFG of Germany (Collaborative Research Center *The Low-Energy Frontier of the Standard Model*, SFB 1044) and by MIUR of Italy (Program *Futuro in Ricerca* 2010, RBFR10O36O).

References

- [1] J. M. Conrad, “Neutrino Experiments,” arXiv:0708.2446 [hep-ex].
- [2] K. N. Abazajian, M. A. Acero, S. K. Agarwalla, A. A. Aguilar-Arevalo, C. H. Albright, S. Antusch, C. A. Argüelles and A. B. Balantekin *et al.*, “Light Sterile Neutrinos: A White Paper,” arXiv:1204.5379 [hep-ph].
- [3] S. N. Gninenko, Phys. Rev. D **83** (2011) 015015. [arXiv:1009.5536 [hep-ph]].
- [4] C. Athanassopoulos *et al.* [LSND Collaboration], Phys. Rev. Lett. **77** (1996) 3082; [arXiv:nucl-ex/9605003]; C. Athanassopoulos *et al.* [LSND Collaboration], Phys. Rev. C **54** (1996) 2685; [arXiv:nucl-ex/9605001]; C. Athanassopoulos *et al.* [LSND Collaboration], Phys. Rev. Lett. **81** (1998) 1774; [arXiv:nucl-ex/9709006]; A. Aguilar *et al.* [LSND Collaboration], Phys. Rev. D **64** (2001) 112007. [arXiv:hep-ex/0104049].
- [5] B. Armbruster *et al.* [KARMEN Collaboration], Phys. Rev. D **65** (2002) 112001. [arXiv:hep-ex/0203021].
- [6] D. McKeen and M. Pospelov, Phys. Rev. D **82** (2010) 113018. [arXiv:1011.3046 [hep-ph]].
- [7] V. Bernard, T. R. Hemmert and U. G. Meissner, Nucl. Phys. A **686** (2001) 290 [arXiv:nucl-th/0001052].
- [8] S. N. Gninenko and N. V. Krasnikov, Phys. Lett. B **450** (1999) 165 [hep-ph/9808370].
- [9] C. J. Horowitz, H. -c. Kim, D. P. Murdock and S. Pollock, Phys. Rev. C **48** (1993) 3078.
- [10] L. F. Li and F. Wilczek, Phys. Rev. D **25** (1982) 143.

- [11] R.N. Mohapatra and P.B. Pal, *Massive Neutrinos in Physics and Astrophysics*, 1991, World Scientific.
- [12] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. D **79** (2009) 072002 [arXiv:0806.1449 [hep-ex]].
- [13] A. A. Aguilar-Arevalo *et al.* [The MiniBooNE Collaboration], Phys. Rev. Lett. **98** (2007) 231801; [arXiv:0704.1500 [hep-ex]]. A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **102** (2009) 101802. [arXiv:0812.2243 [hep-ex]].
- [14] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **103** (2009) 111801 [arXiv:0904.1958 [hep-ex]]; A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **105** (2010) 181801 [arXiv:1007.1150 [hep-ex]].
- [15] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], “A Combined $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Analysis of the MiniBooNE Excesses,” arXiv:1207.4809 [hep-ex].
- [16] O. Benhar and D. Meloni, Nucl. Phys. A **789**, 379 (2007) [hep-ph/0610403]; M. Martini, M. Ericson, G. Chanfray and J. Marteau, Phys. Rev. C **80**, 065501 (2009) [arXiv:0910.2622 [nucl-th]].
- [17] M. C. Martinez, P. Lava, N. Jachowicz, J. Ryckebusch, K. Vantournhout and J. M. Udias, Phys. Rev. C **73** (2006) 024607 [nucl-th/0505008]; J. E. Amaro, M. B. Barbaro, J. A. Caballero, T. W. Donnelly and J. M. Udias, Phys. Rev. D **84** (2011) 033004 [arXiv:1104.5446 [nucl-th]]; J. Nieves, F. Sanchez, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. D **85** (2012) 113008 [arXiv:1204.5404 [hep-ph]].
- [18] K. Abe *et al.* [T2K Collaboration], Nucl. Instrum. Meth. A **659** (2011) 106 [arXiv:1106.1238 [physics.ins-det]].
- [19] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **107** (2011) 041801 [arXiv:1106.2822 [hep-ex]].
- [20] S. N. Gninenko, Phys. Rev. D **85** (2012) 051702 [arXiv:1107.0279 [hep-ph]].
- [21] C. Dib, J. C. Helo, M. Hirsch, S. Kovalenko and I. Schmidt, Phys. Rev. D **85** (2012) 011301 [arXiv:1110.5400 [hep-ph]]; C. Dib, J. C. Helo, S. Kovalenko and I. Schmidt, Phys. Rev. D **84**, 071301 (2011) [arXiv:1105.4664 [hep-ph]].
- [22] C. T. Kullenberg *et al.* [NOMAD Collaboration], Phys. Lett. B **706** (2012) 268 [arXiv:1111.3713 [hep-ex]].

- [23] S. N. Gninenko, Phys. Lett. B **710** (2012) 86 [arXiv:1201.5194 [hep-ph]].
- [24] A. D. Dolgov, S. H. Hansen, G. Raffelt and D. V. Semikoz, Nucl. Phys. B **580** (2000) 331; [arXiv:hep-ph/0002223]. Nucl. Phys. B **590** (2000) 562. [arXiv:hep-ph/0008138].
- [25] M. Masip and P. Masjuan, Phys. Rev. D **83** (2011) 091301 [arXiv:1103.0689 [hep-ph]]; J. I. Illana, P. Lipari, M. Masip and D. Meloni, Astropart. Phys. **34** (2011) 663. arXiv:1010.5084 [astro-ph.HE].
- [26] R. Bernabei *et al.* [DAMA Collaboration], Eur. Phys. J. C **56** (2008) 333 [arXiv:0804.2741 [astro-ph]].
- [27] C. E. Aalseth *et al.* [CoGeNT Collaboration], Phys. Rev. Lett. **106** (2011) 131301 [arXiv:1002.4703 [astro-ph.CO]].
- [28] R. Harnik, J. Kopp and P. A. N. Machado, JCAP **1207** (2012) 026 [arXiv:1202.6073 [hep-ph]].
- [29] M. Pospelov and J. Pradler, Phys. Rev. D **85** (2012) 113016 [arXiv:1203.0545 [hep-ph]].